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Research Article

Effectiveness of eradication measures for the invasive Australian swamp stonecrop *Crassula helmsii*

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Abstract

The amphibious invasive alien *Crassula helmsii* is native to Australasia and introduced in Europe. This species negatively affects wetland ecosystems by outcompeting native species, impeding water flow, reducing dissolved oxygen and stimulating redox processes. Therefore, effective eradication measures are required. However, a comprehensive overview of available eradication measures for *C. helmsii* and an assessment of their effectiveness are lacking. The effectiveness of eradication measures for *C. helmsii* was systematically reviewed. A literature search included scientific journal papers and reports to compile a consistent data set on effectiveness of 59 eradication studies in short-term and long-term. Only measures aiming at complete eradication of the species were assessed and classified (i.e., chemical, mechanical, physical and combined treatments). Effectiveness of these measures was low. Only 10% of the studies reported an effective eradication of the species. Separate and combined eradication measures appeared to be potentially effective immediately after treatment in 32% and 45% of the studies, respectively. However, these measures were only effective in the long-term in 8% and 14% of the studies, respectively. Effectiveness of measures was often insufficiently documented or/and monitored. For instance, information on treated surface area and scale, effects on non-target species and costs of the eradication program was mostly lacking. Eradication measures failed because of species plasticity and adaptation to a wide range of ecosystems. Furthermore, there was a lack of preventive measures against recolonization. Conditions for successful eradication are small-sized area of infestation, presence of the species in a (hydrologically) isolated system and terrestrial growth. Eradication is unlikely if these conditions are not met. Prevention, population control and containment of the species appear to be the only achievable management options in such cases.

Key words: aquatic weed, elimination, negative impact, non-native species, semi-terrestrial growth

Introduction

The amphibious invasive plant species *Crassula helmsii* (Kirk) Cockayne is native to regions of Australasia and introduced in parts of Europe and the United States of America (Dawson and Warman 1987; OEPP/EPPO 2007; CABI 2016). An alien species is considered to be invasive when it threatens biodiversity, functioning of ecosystems or ecosystem services or has a significant adverse impact on human health or the economy (European Commission 2014; Verbrugge et al. 2016). For example, invasive alien plant species may suppress or exclude native plant species by competition for light and nutrients (Vitousek et al. 1997; Levine et al. 2003). Several adverse effects have already been reported after the establishment of *C. helmsii* outside its native range. The species can quickly become dominant on bare soils especially when the location is rich in nutrients (Brouwer et al. 2017) and negatively affect hydrology and water quality (Newman 2013). Dominance by *C. helmsii* has also been found to reduce the number of characteristic species in ponds (Dawson and Warman 1987; Leach and Dawson 1999).

Crassula helmsii is a perennial species with both aquatic and terrestrial growth forms (Funk et al. 2008) that remain green and grow throughout the entire year (Dawson and Warman 1987; Hussner 2008). The species can quickly adapt morphologically to water level fluctuations. The terrestrial growth form is creeping with erect stems and a succulent appearance, whereas submerged forms have stems with longer internodes and have thin leaves, sparsely distributed along the upper stem (Dawson and Warman 1987). Emerged plants produce flowers that yield on average two seeds each which potentially result in generative reproduction (OEPP/EPPO 2007; Denys et al. 2014a; D'hondt et al. 2016). The species colonizes various types of aquatic ecosystems, including moorland and dune pools, small streams, lakes and ponds and their banks (Dawson and Warman 1987; Robert et al. 2013).

Crassula helmsii has been introduced via anthropogenic pathways such as ornamental trade, and escapes from confinement throughout Eurasia (Dawson and Warman 1987; Branquart et al. 2007; EPPO 2007; CABI 2016). The first records of established populations in the wild in Europe were in the UK in 1950, followed by Germany in the early 1980s (Swale and Belcher 1982; OEPP/EPPO 2007). Since then, the spread of the species has significantly increased in the UK (Environment Agency 2003; OEPP/EPPO 2007). A similar trend has been recorded in the Netherlands (Van Kleef et al. 2016, 2017) after its first observation in 1995 (Brouwer and den Hartog 1996; Q-bank 2016).

The rapid growth and spread of *C. helmsii*, in addition to its negative effects on biodiversity and functioning of ecosystems, show the need for eradication measures or at least population control and containment to reduce the environmental impact of the species (OEPP/EPPO 2007). According to the definitions of the European Commission (2014), eradication is the complete and permanent removal of a population of invasive species by lethal or non-lethal means. Population control aims at any lethal or non-lethal action applied to a population of invasive species with the goal of keeping the number of individuals as low as possible. Containment is any action aiming at creating barriers which minimizes the risk of a population of an invasive species dispersing and spreading beyond the invaded area.

Various treatments have been used for eradication, population control and containment of invasive aquatic plant species. These include mechanical, chemical, biological and physical measures, which can also be combined. Prevention and (rapid) eradication of an invasive alien species are regarded as the most cost efficient management action (e.g., European Commission 2014). However, eradication of *C. helmsii* is only feasible under particular circumstances. Recent literature includes several reviews of available eradication, population control, and containment measures for aquatic weeds in general (Genovesi 2005; Kettenring and Adams 2011; Hussner et al. 2017). Much research has been focused on specific types of measures (e.g., biological, chemical, mechanical or physical treatments) for specific species (Gassmann et al. 2006; Sheppard et al. 2006), and an overview of results of multiple studies was also reported for *C. helmsii* (Conservation Evidence 2016). However, a comprehensive overview of available eradication measures for *C. helmsii* and an assessment of their success in the short and long run are lacking (Delbart et al. 2011). Therefore, it is still unclear when and which measures are (potentially) effective and efficient to eradicate this species.

The aim of this research is to systematically review scientific journal papers and reports and to compile a consistent dataset on eradication measures for invasive *C. helmsii* populations in introduced regions. A comparative analysis of separately executed eradication measures and combined treatments was performed to determine criteria for successful eradication, using the available data on short-term and potentially long-term effectiveness, as well as costs and effects on non-target species. Environmental circumstances for successful eradication will be discussed. The outcomes of our quantitative assessment of various eradication efforts can serve to guide future management decisions to counteract spread and impact of *C. helmsii*.

Methods

Data search

A literature search was carried out to compile information from scientific articles and reports on the eradication of *C. helmsii* under field or laboratory conditions. The online literature database Web of Science was searched using the scientific species name as a search term (Supplementary material, Table S1). Google Scholar and Google were used to find additional scientific and grey literature (e.g., reports with data from nature managers). Data from grey literature were included because evaluations of management actions of nature managers are usually published in professional reports, newsletters or management plans.

The species is reported to be invasive or potentially invasive in North-western Europe, including Belgium, Denmark, England, Germany, Ireland, the Netherlands and Scotland (Dawson and Warman 1987; Branquart et al. 2007; EPPO 2007; Delbart et al. 2011; CABI 2016). Therefore, a combination of the scientific species name and Danish, Dutch/Flemish, English or German terms related to the eradication or control of plant populations was used in search queries (for all search terms see Table S1). This search strategy was assumed to produce a good sample of studies dealing with the eradication, control and containment of *C. helmsii*.

Search terms for measures that do not result in data on complete removal per se, i.e. control(ling) and prevent(ion), were included as these terms are not distinctively used in the description of eradication measures against *C. helmsii*. However, only literature aiming at eradication was reviewed. For each search query, the relevance of the first 100 hits was assessed with a quick-scan of the title and summary or abstract. Google Scholar ranked the hits based on their relevance to the performed query through determining publication location, authors, recent citations, and the number of citations (Google Scholar 2016). In cases with fewer hits all retrieved papers were assessed (e.g., in the search queries using Web of Science). Table S1 shows the results of the search and selection process for suitable literature.

Data treatment

A dataset was constructed with the relevant information concerning eradication effort from scientific papers and reports on eradication measures for *C. helmsii* (Table S2). The classification of the extracted information included the following themes and criteria for assessment of these efforts:

1. Area and country: geographic location of executed measures against *C. helmsii*. At each location a treatment with either one or a combination of consecutive measures against *C. helmsii* was carried out.
2. Year in which measures were executed.
3. Water type as described in literature: lake, ditch, river wetland, pond, coastal wetland, canal, former salt pans, infiltration canal or laboratory set up.
4. Dimension of the water system and proportion of the area infested with the species: if available, both areas were quantified (e.g., m^2, ha) or qualified (e.g., wide spread population).
5. The measure category: e.g., chemical, mechanical or physical;
6. The type of eradication measure(s): e.g., herbicide application, mechanical sod-cutting or desiccation by drainage.
7. Means used per measure: e.g., a particular product, dosage, machine or material;
8. Duration of treatment: number of months during which all measures have been executed.
9. Frequency of measures: number of repetitions.
10. Measures executed to prevent recolonization, spread or new introductions: e.g., transportation of removed plants to a processing company or isolation of the water system from other water bodies to prevent spread of plants or fragments by water flow.
11. Reported side effects of measures: e.g., biodiversity reduction or changes in plant communities.
12. Costs of treatment: in euros.
13. Classification of treatment effectiveness: the executed measures were classified into four groups based on reported results.
    i. Effective in the short-term, i.e. *C. helmsii* was completely removed directly after the eradication effort and was not observed within one growing season (i.e. one year),
    ii. Ineffective in the short-term, i.e. *C. helmsii* was not completely removed directly after the eradication effort or was present again within one growing season,
    iii. Potentially effective in the long-term, i.e. *C. helmsii* was not present after multiple growing seasons. Note that it was not possible to identify effectiveness in the long-term because available post-intervention surveys lasted one to 19 years and uncertainty concerning persistence of seed banks. However, owing to high biomass productivity and year round growth it may be assumed that the eradication is potentially effective on the long-term when the species has not been observed after one or multiple growing seasons,
    iv. Ineffective during multiple growing seasons, i.e. *C. helmsii* was present after one year due to re-introduction or regrowth.
14. References.

Chemical, mechanical and physical measures were excluded from analysis if these were only applied for population control or containment and did not explicitly aim at eradication. Ineffective measures in the short-term were assumed to be ineffective in the long-term as well. Information on side effects was not considered when scoring the effectiveness of eradication measures. Reported negative and positive effects on native species and nature conservation targets were separately assessed.

Table 1. Studies reporting combinations of two or more eradication measures for *Crassula helmsii.*

No.	Measures [a]	Short-term success	Potentially long-term success	Reference [c]
1	Herbicide application, twice (C)	No	No	1
2	Herbicide application, twice (C) [b]	No	No	2
3	Mechanical-sod-cutting (M), removal by hand (M)	Yes	Not recorded	3
4	Removal by hand (M), light limitation (coverage, P)	Not recorded	Not recorded	4
5	Mowing (M), light limitation (coverage, P)	Yes	No	5
6	Removal by hand (M), light limitation (coverage, P)	Yes	Not recorded	5
7	Draining (P), salinization (P)	Yes	Yes	6
8	Draining (P), salinization (P)	Yes	Not recorded	6
9	Draining (P), mechanical-sod-cutting (M)	No	No	3
10	Draining (P), mechanical-sod-cutting (M)	Not recorded	Not recorded	3
11	Burning (fire, P), mechanical-sod-cutting (M)	Yes	Not recorded	3
12	Draining (P), mechanical-sod-cutting (M)	Yes	Yes	3
13	Herbicide application, twice (C), light limitation (coverage, P)	No	No	7
14	Herbicide application, twice (C), light limitation (coverage, P)	Not recorded	Not recorded	8
15	Draining (P), herbicide application (C), filling up (M)	Yes	Yes	9
16	Mowing (M), light limitation (coverage, P), removal by hand (M)	No	No	5
17	Draining (P), herbicide application (C), mechanical-digging (M)	No	No	10
18	Light limitation (coverage, P), herbicide application (C), removal by hand (M)	Yes	Not recorded	10
19	Herbicide application, four-times (C)	Yes	No	11
20	Salinization (field, C), draining (P), mechanical-sod-cutting (M), removal by hand (M)	No	No	5
21	Draining (P), mechanical-digging (M), light limitation (coverage, P), light limitation (colouring agent, P), removal by hand (M)	No	No	12
22	Removal by hand (M), burning (fire, P), draining (P), mechanical-digging (M), light limitation (coverage, P), removal by hand (M)	No	No	5

[a] C: chemical, M: mechanical, P: physical. [b] Laboratory study. [c] References: 1. Child and Spencer-Jones 1995, 2. Dawson and Henville 1991, 3. Boute 2013, 4. Adriaens et al. 2010, 5. Torensma 2017, 6. Charlton et al. 2010, 7. Stone 2002, 8. Anonymous 2014, 9. Sims and Sims 2016, 10. CAISIE 2013, 11. Spencer-Jones 1994, 12. Denys et al. 2014b.

The dataset was quantitatively explored to elucidate success factors for eradication of the species classifying them into short-term effectiveness and potentially long-term effectiveness. The number and repetition of measures were taken into account. Additionally, the overall short-term and long-term effectiveness was compared between treatments with separately performed and combined measures. Furthermore, the type of effects on non-target species and the costs of executed eradication measures were recorded, including the amount of times this information was reported.

Results

Data was extracted from 71 available sources that reported eradication efforts against *C. helmsii*. However, some sources reported multiple publications on results of the same project (e.g. as journal paper and report) and others were targeted at control or containment measures. In total, 59 studies were relevant for our research aim and were systematically reviewed and classified based on short-term and potentially long-term effectiveness (complete or partial removal of populations) of management measures. At 37 sites one measure was executed, whereas two or more consecutive measures were performed at 22 sites. These studies concern field setups in Belgium, Ireland, the Netherlands and the UK. In the UK also six laboratory studies have been reported. Our search strategy did not yield suitable publications for Germany or Denmark.

Eradication measures

Figure 1 shows the classification of treatments reported in 37 studies into 11 different types of eradication measures that have been singularly applied to *C. helmsii* populations. The application of herbicides and salt water have been performed in laboratory (n = 7) and field setups (n = 18). Measures aiming at complete eradication of the species were classified as chemical, mechanical and physical treatments (14, 10 and 13 studies, respectively).

Twenty-two additional studies reported treatments that combined two or more eradication measures (Table 1). Physical and mechanical measures were the most common approaches to be combined. Chemical treatments were frequently combined with other (repetitive) chemical and physical measures.

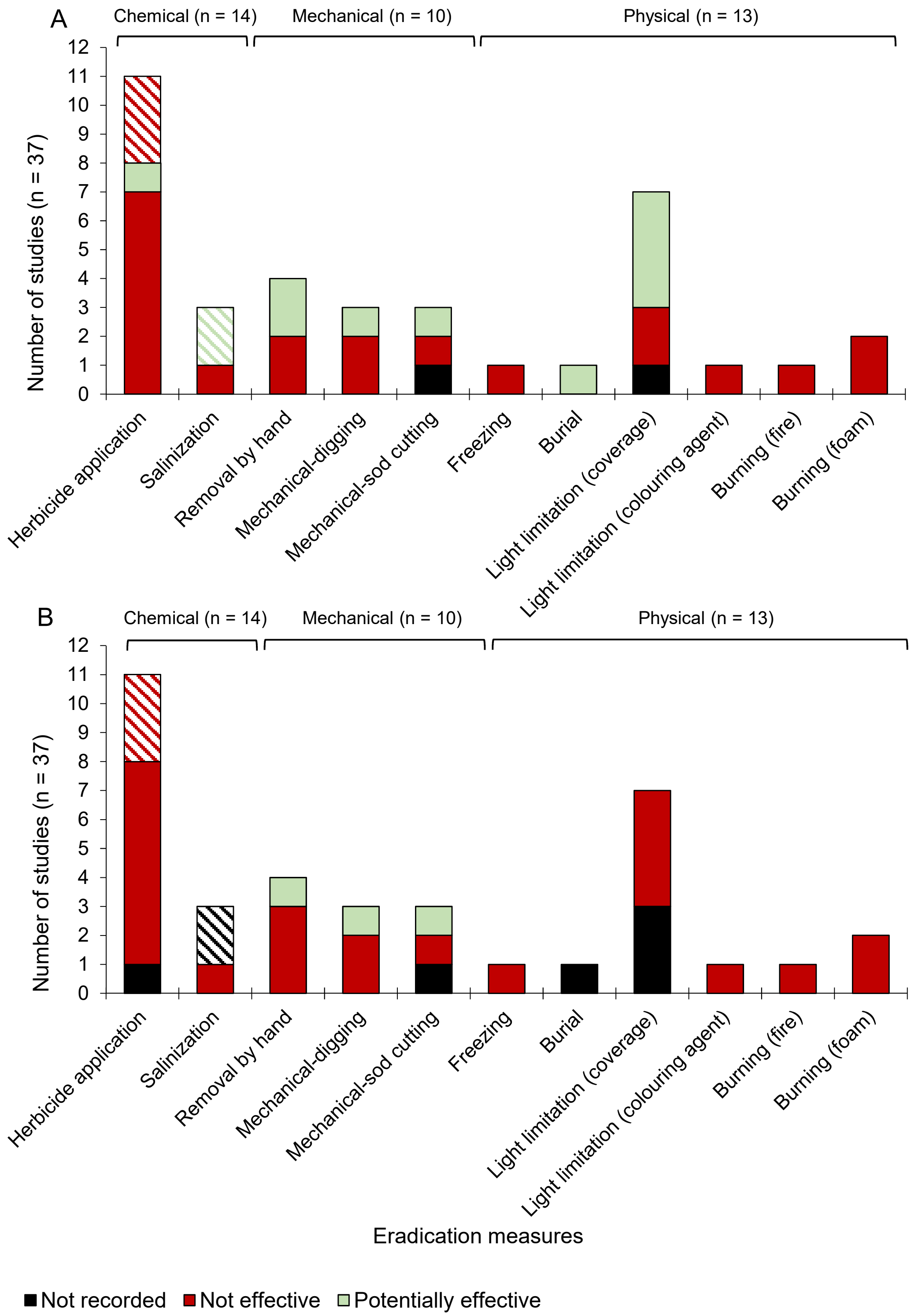

Figure 1. The number of various types of separately executed eradication measures (n = 37) for *Crassula helmsii* with 100% effectiveness (green), less than 100% effectiveness (red) and a lack of information on effectiveness (grey) in A) short-term (directly after execution of the measures or within at least one year), and in B) potentially long-term (> one year) laboratory and field setups. Diagonal stripes represent studies performed in the laboratory.

Chemical measures

Several herbicides have been applied in field and laboratory experiments to chemically eradicate *C. helmsii* (Figure 1, Table S2 and Table S3). None of the separately performed measures using herbicides were effective in the long-term (Figure 1), and only one of the combined measures including herbicides was successful at eliminating the species (Sims and Sims 2016). The choice of a herbicide depends on the effects and suitability of conditions for application. Glyphosate and diquat are non-specific herbicides which inhibit plant growth and reduce plant biomass. Glyphosate is best applied on emerged plants during a period with low water level (Robert et al. 2013). Submersed plants can be treated with diquat (Robert et al. 2013). In some studies, the excipient alginate has been additionally used to realize a better adhesion of the herbicide to the plant (Barrett 1981). The herbicides 2,4-D amine, asulam, dalapon, dichlobenil and terbutryn have modes of action that only affect specific plant tissues. For instance, dichlobenil disrupts the production of cellulose, which reduces plant fitness (Mélida et al. 2010). A risk of herbicide use is decay of large quantities of dead plants. When using herbicides it is necessary to remove all decaying plant material to avoid harmful oxygen depletion in the water by decomposition processes (Robert et al. 2013).

Another chemical treatment is salinization which induces stress due to the intolerance of the plant to long-term exposure of high salinity levels. In addition to relatively short laboratory experiments, wetlands have been salinized for 6 to 12 months in order to eradicate *C. helmsii* (Charlton et al. 2010; Dean et al. 2013; Torensma 2017). Although these treatments were effective in laboratory experiments, their effectiveness in the field varied. The field studies were performed in coastal wetlands with ready access to salt water. First, the water bodies infested with *C. helmsii* were drained by pumps during low tide. Subsequently, during high tide, sea water was pumped into them up to a minimum level of 5 cm above the vegetation.

Mechanical measures

Several mechanical measures have been applied to remove *C. helmsii*, such as digging, sod-cutting and mowing by hand or machines in combination with other measures (Figure 1 and Table S2). Both submerged and emerged plants were treated. Mechanical measures can contribute to the fragmentation and spread of plants, thereby posing a risk for regrowth in the treated area and colonisation of new areas (Dawson and Warman 1987; OEPP/EPPO 2007; Denys et al. 2014b). Therefore, it is necessary to remove all plant material from machines and other equipment when applying mechanical measures for eradication of *C. helmsii.*

Infestations have been excavated manually, up to 40 cm in soil depth, to remove all visible parts of plants and roots of small populations (< 1 m^2 cover) (Dawson and Henville 1991; Adriaens et al. 2010; Boute 2013; Torensma 2017). This measure demonstrated potentially long-term effectiveness at one location (Torensma 2017). Adverse side effects of manual excavation on non-target native species are reported to be negligible, but this measure is labour intensive.

On a larger scale, excavators have been used to remove top soil (> 25 cm) covered with *C. helmsii* (Leach and Dawson 1999; Adriaens et al. 2010; Boute 2013). This measure was reported to be effective at one location when performed separately and at another one when performed in combination with drainage of the water body (Leach and Dawson 1999; Boute 2013). Using this approach, the seed bank of non-target plants and most fauna will also be removed together with the aboveground and belowground biomass of *C. helmsii*.

Sod-cutting has also been used to remove *C. helmsii* from banks (Adriaens et al. 2010; Boute 2013; Denys et al. 2014b; Torensma 2017). This measure was effective for the removal of a small infestation (up to circa 0.2 ha) (Torensma 2017). In contrast to excavation, sod-cutting only removes a few centimetres of the top soil by using a shovel or an excavator. The effectiveness of this measure depends on the depth of sod-cutting which is dependent on the type of the soil substrate and depth of roots. Sod-cutting on a clay soil is more challenging than on a sandy soil and deep growing roots can cause regrowth of plants (Adriaens et al. 2010). Side effects of sod-cutting are similar to excavation.

Physical measures

Physical eradication measures consisted of light limitation (covering and dying), exposure to lethal temperature conditions (burning and freezing), desiccation (drought by drainage) and suffocation by burial (Figure 1 and Table S2).

A reduction of light limits photosynthesis efficiency and may cause inhibition of growth, eventually leading to mortality of plants. Executed measures are the coverage of shores with black tarpaulin or burlap mats and the addition of colouring agents to waters infested with *C. helmsii* (Dawson and Warman 1987; Bridge 2005; Wilton-Jones 2005; Adriaens et al. 2010; CAISIE 2013; Denys et al. 2014b; Ewald 2014; Torensma 2017). Seven efforts were effective in the short-term. None of these efforts was effective in the long-term. The tarpaulin or mats are more effective the longer they cover infested areas, with a minimum duration of at least two months (Robert et al. 2013). However, in some cases regrowth of the species was observed in areas with a five year coverage of black tarpaulin in the Netherlands (author's personal observation 2017). This may be attributed to regrowth of surviving fragments, germination of seeds or recolonization (dispersal from other areas). The influences of burial or storage condition on seed viability are still unknown. The use of covers causes a disruption in the ecosystem (OEPP/EPPO 2007; Robert et al. 2013). Therefore, this measure has severe effects on non-target species. In two field studies red, blue and black colouring agents (Dyofix) were added to a pool and pond to limit incidence of light and stop photosynthesis (Denys et al. 2014b; Ewald 2014; Torensma 2017). In addition to colouration of the water layer, plants that grow in shallow littoral zones or on semi-aquatic banks should be eradicated by other means because dyes are not effective in shallow water because the light reduction is not effectively preventing or limiting photosynthesis (Boute 2013; Denys et al. 2014a). The success rate is further reduced because plants increase their internode length and grow towards the water surface to escape from the darkness, causing stems to be more prone to breaking thereby increasing propagule pressure on the bank and water level fluctuations that cause plants to emerge from the water column (Boute 2013).

Freezing plants with liquid nitrogen is effective when treating the complete plant and has limited impacts on non-target species. However, application of this treatment on a large scale would be difficult and it is very labour intensive to treat all plants (Leach and Dawson 1999). On three locations flamethrowers have been used to combat *C. helmsii* (Leach and Dawson 1999; Boute 2013; Torensma 2017). Even though the application is relatively easy, this method only scorches aboveground plant tissues and does not generate enough heat to kill the roots and to prevent regrowth (Dawson and Henville 1991). If applied specifically on individuals of *C. helmsii* it has limited effects on non-target species. However, when large areas are treated by fire, non-target species are also harmed. The same applies for hot foam measures (Waipuna) (Bridge 2005; Bogaert 2013; Ewald 2014). In the long-term, these three measures either fail or their effectiveness for eradication is unknown. Using fire was once reported as effective in the short-term.

Desiccation by drainage of a water body has also been performed to eradicate the species. It is essential to use an appropriate filter and sieve during the draining process in order to prevent the spread of plant fragments to new locations (Denys et al. 2014b). This measure is usually executed in combination with mechanical measures (excavation or sod-cutting), chemical measures (the use of herbicides or salt) or other physical measures (e.g. light limitation) (Charlton et al. 2010; Gardiner and Charlton 2012; Boute 2013; CAISIE 2013; Denys et al. 2014b; Millane and Caffrey 2014; Torensma 2017). Potential long-term effective eradication has been achieved multiple times when drainage was combined with other measures (Charlton et al. 2010; Boute 2013; Sims and Sims 2016). However, complete drainage of a water body is not feasible if seepage and or rain fall are high. This measure may have adverse side effects on aquatic non-target native species which are also effected by drought (Torensma 2017; author's personal observation 2017). However, the measure could be beneficial in waters by oxygenating the soil and thereby reducing eutrophication and stimulating the germination of non-target species (Roelofs and Bloemendaal 1988; Kok et al. 1990).

In situ burial resulting in suffocation has been used once to eradicate *C. helmsii* in small water bodies such as ponds (Sims and Sims 2016). This measure was combined with drainage and the use of herbicides. On one location, a complete lake was filled with sediment to eradicate the species (Boute 2013). This comprehensive approach was carried out because previously executed chemical and mechanical measures were insufficient. Monitoring data on effectiveness in the long-term are not available. After drainage, a pond can be filled by on-site material. This method changes the landscape and adversely affects all non-target species on site. Nevertheless, this measure may be applicable when ponds or small lakes have a low conservation value and protected or endangered species are not present.

Effectiveness of measures

Short- and potentially long-term ineffectiveness of separately executed eradication measures for *C. helmsii* was 62% and 70%, respectively (Figures 1 and 2A). In 32% (n = 12) of the studies reporting single measures, eradication was complete directly after the treatment, or within one year, with one of the following seven measures: mechanical digging, mechanical sod-cutting, removal by hand, burying by filling up the water body, light limitation by black tarpaulin coverage, salinization (laboratory study) and application of herbicides (Figure 1A).Three (8%) of these successful short-term measures were effective in the long-term. These were mechanical-digging, mechanical-sod-cutting and removal by hand (Figure 1B).

In total, 45% of the studies that combined multiple measures were effective in complete eradication of *C. helmsii* directly after application or within one year (Figure 2B). These studies were a combination of multiple types of measures: burning and sod-cutting (Boute 2013), light limitation with burlap mats and the use of the herbicide glyphosate (CAISIE 2013), a combination of sod-cutting and removal by hand (Boute 2013), removal by hand and light limitation by covering (Torensma 2017), and the application of multiple herbicides (dichlobenil, terbutryn and diquat alginate) (Spencer-Jones 1994). Three studies reported a potentially effective eradication of *C. helmsii* populations in the long-term by combining multiple measures: (i) a once-only drainage of the water body resulting in suffocation, excavation of the soil and removal of plant material from the location (Boute 2013), (ii) drainage of the water body and salinization for nine months, and (iii) drainage of the water body, herbicide application (glyphosate) and burial by filling up the water bodies with soil (Sims and Sims 2016). The number of studies with an unknown success in the long-term are 22% and 32% for separately executed measures and combined measures, respectively (Figure 2).

Only a few studies (10%) resulted in a potentially effective eradication of the plant species. Potentially effective eradication in the long-term by single measures were: removal by hand in Leenderheide, the Netherlands (Torensma 2017), mechanical digging in Liverpool, the UK (Leach and Dawson 1999) and mechanical sod-cutting in Ruinen, the Netherlands (Torensma 2017). Separate measures were only effective in the long-term when the aboveground and belowground biomass of the plant was completely removed. The long-term effectiveness was higher when measures were combined. Successful combined eradication efforts were; drainage combined with salt water inundation in Bedfordshire (Irongate Field), the UK (Charlton et al. 2010), drainage, herbicide application and infilling of the pond in Norwich, the UK (Sims and Sims 2016), and drainage and mechanical digging of banks in Roosendaal, the Netherlands (Boute 2013). In all of these treatments the infected area was drained prior to further measures.

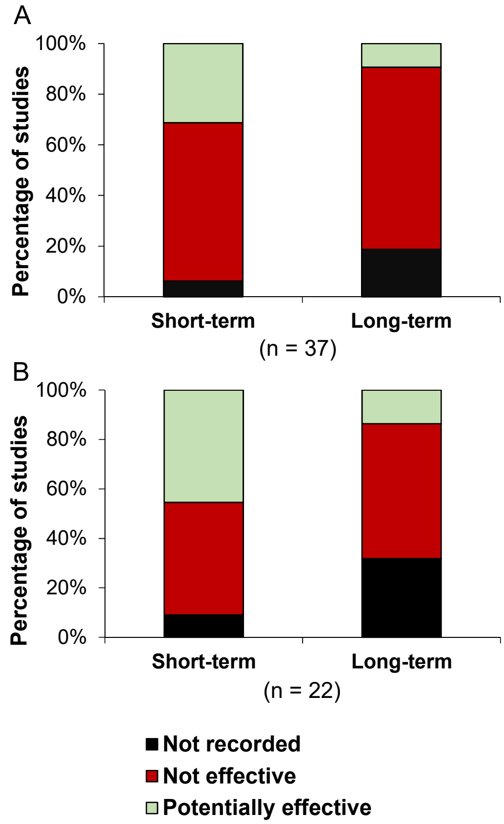

Figure 2. The effectiveness of treatments with one or a combination of multiple eradication measures against *Crassula helmsii* (%) in short-term (directly after execution of the measures or within at least one year) and potentially long-term (> one year) laboratory and field setups. A) individually performed measures, B) combination of ≥ 2 measures.

Effects of measures on non-target species

Side effects are reported for only 30% of the executed eradication measures. Effects on non-target species largely depend on the scale of measures (e.g., local scale versus landscape scale) and the time since the treatment (e.g., population declines immediately after treatment versus recovery of non-target species on the long run). Negative effects on the structure and functioning of communities were reported for light limitation by coverage, salinization and excavation (Leach and Dawson 1999; Bridge 2005; Dean et al. 2013; Dean 2015). The application of herbicides combined with other measures, such as light limitation by coverage, desiccation by drainage, and sod-cutting, resulted in disturbances of the ecosystem and degradation of native vegetation (Child and Spencer-Jones 1995; CAISIE 2013; Millane and Caffrey 2014). The duration and timing of these side effects were not reported.

Positive effects were reported for the combination of drainage and salinization measures (Charlton et al. 2010; Gardiner and Charlton 2012). These measures resulted in the recolonization of rare plant species in the years following the treatment, whereas no harmful effects on terrestrial insects were noticed.

In two treated sites, changes in biomass and diversity of native vegetation were reported. These changes were considered to be neither positive nor negative. Drainage, excavation, light limitation by coverage and addition of colouring agents to a pool was reported to increase the abundance of *Drepanocladus aduncus* and *Myriophyllum spicatum* and decrease the presence of *Potamogeton obtusifolius*, *P. pusillus* and *Chara virgata* (Denys et al. 2014b). Salinization of a coastal area reduced the native vegetation cover from 75% to 30%, but had little influence on invertebrate species which were already present in low abundances (Charlton et al. 2010). However, in other studies salinization resulted in a reduction of invertebrate species (Marshall and Bailey 2004).

Costs of measures

Reported information on the costs of eradication measures is scarce. Only 8% (n = 5) of the studies reported on the costs incurred. A combination of light limitation by coverage and herbicide (glyphosate) application to a low density population of *C. helmsii* on three different locations in Ireland amounted to a total of €1,533,466,- (CAISIE 2013). Measures were performed in Derrymoyle Bay (175 km^2) and Grand Canal (2.5 km in length) in Ireland, however, the exact surface areas of the treated sites were not reported. The costs of drainage and salinization of multiple ponds and shallow grazing marshes, in total 120 ha, in a coastal wetland in Bedfordshire (UK), are €9,930. This includes a field survey on the spread of the species before the intervention and monitoring afterwards (Charlton et al. 2010; Gardiner and Charlton 2012). The costs of plant removal by gas-flamethrowers were estimated at €11,000–17,478 per ha for ponds in Hampshire, the UK (Leach and Dawson 1999).

Discussion

Data availability and certainty

Our database contains information on a wide variety of eradication measures for the species that have been executed in the field or laboratory during the period 1987–2017 (Table S2). The water type, used measure(s) (i.e., category, type and means) and qualitative or quantitative results of the treatment with one or a combination of measures is included for all studies. This data was sufficient to classify the effectiveness of treatments in the short-term and long-term.

The database is mostly lacking information on the surface area of the treated locations, scale at which a measure was applied, coverage and biomass of the *C. helmsii* population, effects on non-target species and costs of measures. Therefore, it was not possible to derive useful standard classifications of this data. This information is necessary for future decision making on the suitability of measures because it provides insights into the effectiveness of performed measures. Additionally, with this data it is possible to place eradication efforts in perspective. This can result in an analysis of required conditions for effective eradication programs. In turn, a lack of this data ensures an incomplete overview of reported eradication efforts which cannot be reliably used for other cases of infections. According to Blossey (1999), monitoring the effects of invasive plant species management should go beyond “simple” impacts on plant communities and must also incorporate information about different taxa and trophic levels, e.g. net primary production, plant diversity, fauna communities among other abiotic and biotic conditions.

Multiannual monitoring of executed measures is not generally performed. Information on regrowth of *C. helmsii* in treated areas is often lacking. As a result, it is unclear for many studies whether the species has repopulated the treated area and thus if the measures are potentially effective in the long-term. Therefore, in this review long-term success is defined as the plant not being recorded during a minimum period of one year after execution of the measure(s). However, in the period following that first year the environment is still vulnerable for regrowth due to remaining propagules, viable seeds or recolonization of the species. Small patches, that have survived eradication measures, are easily missed during monitoring. A monitoring period of five years will yield a more reliable result of the long-term eradication success.

Cause of effectiveness and failure

Potential effectiveness or failure of (a combination of) measures to eradicate invasive species is always context dependent. Successful separate eradication measures aimed at active removal of relatively small infestations, i.e., 1.0 ha in Leenderheide, 0.2 ha in Ruinen, and an unspecified site in Liverpool (Table S2), from isolated water systems, such as ponds. Drainage was performed in all treatments with combined measures that resulted in 100% effective eradication. Both separately performed and combined measures were executed above water. So far, no measures have been reported to effectively eradicate submerged individuals of the species. In most potentially effective measures factors such as isolated water system (five out of six studies; see Table S2), small population size (three out of six studies) and drainage of water (three out of six studies) contributed to a high eradication success. However, these conditions are not always present or feasible to control at an invaded area. To date, the eradication of large populations in large water bodies where water levels cannot be manipulated have not been successful. The success of *C. helmsii* eradication is therefore related to the species' abundance, scale of spread and type of landscape. In such cases it might be necessary to focus either on control or containment. The present literature search was focused on North-western Europe. A web-based information system (GT-IBMA 2016) and recent review by Dortel and Dutartre (2018) report applications of similar measures for eradication of *C. helmsii* in France. These sources confirm that eradication appears only to be effective in small and isolated localities and is difficult to achieve in large and (hydrologically) connected sites.

To a large extent, the species itself causes eradication measures to fail. The species shows high plasticity in characteristics such the photosynthetic mechanisms (switching between CAM and C3), stem and leaf morphology, and it is adapted to grow in a wide range of nutrient levels. These traits give the species the ability to invade various water types (Dawson and Warman 1987; Newman and Raven 1995; Hussner 2009). Due to the ease at which the plant can reproduce by fragmentation as well as seed production, viable propagules can remain after eradication and may recolonize treated areas (Dawson and Warman 1987; Denys et al. 2014a). In several cases, the species was more abundant after a treatment due to the following causes: incomplete eradication, spread of plant or fragments and the creation of a more suitable habitat with bare soil, and a lack of competitive species (J. van der Loop, personal observation).

The failure of eradication measures may also be related to the vectors which introduced the species in the first place. Spread mainly occurs via the dispersal of vegetative plant fragments by water currents (hydrochory) or attached to animals (epizoochory) (Dawson and Warman 1987; Denys et al. 2014a; CABI 2016). Intentional introduction or unintentional spread of *C. helmsii* can be caused by attachment to boots, machines or materials (antropochory) as well (Figuerola and Green 2002; Denys et al. 2014a; Dortel and Dutartre 2018). Preventive measures to reduce the risk of recolonization and spread when performing eradication measures are seldom incorporated. For example equipment such as excavators, mowers, trucks, nets and boots must be cleaned after use and checked for any remaining plant material. Only 40% of the field research studies included preventive measures, yet without reporting their effectiveness. These measures mainly aimed at safe disposal of the collected plant material to a compost facility or storage (Adriaens et al. 2010; Boute 2013; Denys et al. 2014b; Torensma 2017). Other interventions to prevent spread in flowing waterways are building dams, placing nets or using hay bales as filters to prevent the downstream drift of plants or fragments (Siebel and Van Valkenburg 2013; Torensma 2017). Additionally, fences or wires can be placed around or above *C. helmsii* populations to reduce the risk of spread by animals, e.g., livestock and birds (Denys et al. 2014b). The application of these containment measures in addition to elimination treatments should result in a lower re-infection risk and therefore a higher eradication success of the species.

Some eradication measures are difficult to execute and thus have a higher risk of failure. For example, it is challenging to keep salt concentrations high enough for effective salinization due to the influx of rainwater and groundwater (Torensma 2017). For some chemical and physical measures, e.g., applying herbicides or burning, it can be difficult to treat both the aboveground and belowground plant parts to prevent regrowth of unaffected plant fragments. Furthermore, only few of the previously used pesticides are approved for usage in the European Union under Regulation (EC) No 1107/2009, i.e., 2,4-D amine, diquat, glyphosate and hydrogen peroxide (European Commission 2017). These chemicals are not typically allowed for usage in aquatic ecosystems without an exemption, because it can adversely affect (ground) water and drinking water quality. On the contrary, large scale excavation activities can be combined with nature restoration, e.g., by re-profiling banks or creating open spaces for landscape heterogeneity, which in turn provides opportunities for the establishment of specific, nutrient poor vegetation.

This study shows a lack of multiannual monitoring and aftercare of threatened areas, which could also contribute to the failure of eradication measures. Shoots of *C. helmsii* may be capable of arising from "visibly dead" material. The possible establishment of new populations will go unnoticed, and hence left untreated.

Control and containment measures

Although many treatments failed to completely eradicate *C. helmsii*, the executed measures are still potentially useful to control the population and contain its dispersal. Most of the ineffective measures achieved some biomass reduction (Table S2). Activities such as mowing and grazing could lower the plant' biomass, thereby controlling the population size and decreasing the risk of secondary spread (Dawson and Warman 1987; Diaz 2012; Dean et al. 2015). Grazers could, however, also increase the abundance of species by consuming competitive plant species or by acting as a vector for further spread of plant fragments (Robert et al. 2013; Dean et al. 2015). Population control measures mainly target the effects of the species' infestation (e.g., by reducing its dominance in favour of native species) and continuous management efforts will be necessary. This results in recurring costs and possible negative effects on the threatened ecosystems.

Recommendations and further research

It is recommended to systematically monitor and report results of eradication efforts against *C. helmsii* and other invasive species to reduce data gaps on factors such as treated population size, costs, effects on non-target species and spread to surrounding areas. This knowledge is essential to determine the cost-effectiveness of measures and to evaluate eradication measures. Our assessment criteria can be used as a guideline for design of monitoring programs. Monitoring should preferably be performed for five consecutive years, because this will allow detection of slowly expanding and difficult to detect infestations (e.g., regrowth of small spouts or seedlings). There is a high probability of overlooking small propagules which could recolonize the treated area or spread to new areas.

The best way to reduce the probability that an introduced species will become invasive is to eliminate it before it has time to become abundant and widespread (Allendorf and Lundquist 2003). So, prevention of spread is of vital importance when preforming eradication measures for the species. Carefully cleaning equipment and fencing off areas to exclude people, livestock and other animals reduces the risk of recolonization and spread.

Eradication of *C. helmsii*, as well as other widespread invasive species, is often not feasible. At the same time, application of eradication techniques for population control is often undesirable due to the repetitive nature and negative effects on native species. Novel approaches for invasive species control are needed. Biological or system-based measures may provide a beneficial alternative to traditional management tools. Possibilities and effectiveness of these types of measures should be further explored. Currently, biological control experiments of *C. helmsii* are developed by intending to release a gall-forming eriophyid mite in the UK (Varia et al. 2011; Varia et al. 2017). This biocontrol agent acts as a natural enemy which could reduce the plants' biomass. A system-based approach is probably a viable option for a sustainable and cost-effective control of the species. This theory aims at reducing resource availability by manipulating resources as well as presence of other species using the same resources (Dawson and Warman 1987; Hobbs and Huenneke 1992; Funk et al. 2008).

Apart from investigating these novel approaches it is recommended to perform more research on environmental factors determining productivity and reproductive capacity of the species. For example, the effects of environmental factors on viability of the seeds under field conditions is still unknown, limiting assessments of eradication measures on the long run.

Conclusion

Overall, the effectiveness of eradication measures targeting *C. helmsii* is low. Eradication can still be achieved, but only at a local scale and if appropriate methods are applied. Suitable conditions for successful eradication of this species are 1) small-sized infestations, 2) presence in an isolated system, and 3) growth in terrestrial habitat. Eradication is unlikely for large infestations, populations in open water systems or submerged growth without possibilities for drainage of the water body. Population control and containment appear to be the current management approaches for these cases. However, the success rate of measures depends on site specific factors. Therefore, possibilities of eradication efforts must be assessed in site specific context in order to select best measures. Appropriate documentation of management measures and monitoring of their cost-effectivity are vital for improvements of eradication and control programmes of *C. helmsii* and other invasive species.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Used literature search engines and queries, resulting in a number of (relevant) eradication measures for *Crassula helmsii.*

Table S2. Available scientific data on eradication measures for *Crassula helmsii*.

Table S3. Chemical treatments for eradication of *Crassula helmsii*.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2018/Supplements/MBI_2018_Loop_etal_SupplementaryTables.xlsx